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MECHANICAL PERFORMANCE OF POLYPROPYLENE FIBRE REINFORCED MORTAR INCORPORATING PALM OIL FUEL ASH

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Abstract: The performance of Fibre Reinforced Mortar (FRM) mixed with microfine size Palm Oil Fuel Ash was investigated in this study (POFA). The ideal volume of POFA and fibre in the mixed mortar is calculated in order to generate a cost-effective high-strength mortar with increased ductility. In this experimental investigation the polypropylene fibre used ranged from 0 kg/m^3 to 20 kg/m^3 and the replacement of cement with microfine POFA content of 0% and 40% (optimum) was studied. The mechanical properties of fibre reinforced masonry in the presence of the POFA was tested using compressive strength, flexural and split tensile tests. The surface morphology of the fibre reinforced mortar was studied using scanning electron microscopy (SEM) which showed the good fibre-mortar bond in the morphology of the samples at 7 and 28 days. From the compressive strength results, FRM tester contains 40% microfine POFA as a replacement against cement mixed with 10 kg/m^3 of polypropylene fibre is optimum and achieved compressive strength up to 79.5 MPa at the 56th day of curing. Ductility ratio up to 13.3 was achieved from the flexural test for FRM sample with 15 kg/m^3 polypropylene fibres. The high strength FRM with inclusion of POFA as supplementary cementitious material had the potential to become a new sustainable material in construction.

Keywords: Microfine POFA, polypropylene fibre, ductility ratio.

Introduction

Concrete is in high demand, which means cement is in high demand as well. This has resulted in a decrease in natural deposits as well as environmental disruption. A new or improved material to be employed as a substitute in ordinary concrete is required. Malaysia currently produces half of the world's total palm oil supply which is expected to climb as global demand for vegetable oil rises. This industry generates many by-products such as empty fruit bunches, kernel shells and fibres which can be used as fuel for electricity generation.

Palm Oil Fuel Ash is a type of ash that is produced as a by-product of this operation (POFA). Previous studies (Kroehong *et al.,* 2011; Muthusamy *et al.,* 2019) have revealed that this agro-waste includes a high amount of silica and hence has pozzolanic qualities, making it a viable alternative to cement. Recent research has shown that POFA could be used as a partial cement replacement material in the production of high-strength concrete with improved strength and permeability. High Strength Mortar (HSM) mixed with pozzolanic materials such as silica fume (SF), palm oil fuel ash (POFA) and calcined diatomite powder (CDP) can obtain a strength of 108 MPa and 105 MPa after 90 days, according to studies (Dembovska *et al.,* 2017; Mustafa *et al.,* 2020).

Concrete, however, is an inherently brittle material due to its low tensile strength. There are many studies according to Shi *et al.* (2016) and Kim *et al.* (2018) on new technologies to improve the properties of concrete. The creation of High Strength Fibre Reinforced Cementitious Mortar (HSFRCM) is one of the latest developments (Graybeal, 2008; Rebentrost *et al.,* 2008). Though the usage of some type of fibres has been limited due to its production cost.

The materials have been used successfully in the rehabilitation of existing conventional concrete structures, after applying a thin layer of Fibre Reinforced Mortar (FRM) to improve some of its mechanical properties.

In a previous study which was conducted by Fladr and Bily (2018), the fibre added to the concrete mix increased its flexural strength. Alsadey and Salem (2016) found that an increase in the volume ratio of polypropylene fibre content resulted in an increase in its compressive strength. Najimi *et al.* (2009) studied the effects of using polypropylene fibre on the physical and mechanical properties when using fibres of variable lengths, 6 mm, 9 mm and 12 mm.

The results of this study showed an increase in the flexural strength of concrete and a decrease in the width of cracks although, there was a slight decrease in the compressive strength. Furthermore, increasing the volume ratio of polypropylene fibre increased its ductility and compressive strength (Mohamed, 2006).

Thus, it can be concluded that the use of polypropylene fibre in addition to supplementary cementitious material can improve the strength of the concrete.

According to Shi *et al.* (2016), the addition of polypropylene fibre (as much as 0.12% by volume) has significantly improved the cracking constraints in terms of toughness and stiffness cracking. Also adding fibre to the concrete mixture along with POFA resulted in an increase in its strength and made it more economical.

A similar conclusion was made by Chaturvedi and Khan (2016), they specified that the use of 11 numbers of steel and glass fibre with the replacement of 15% POFA into the mixture will give it better strength. Prasad *et al.* (2013) conducted experiments on concrete containing polypropylene fibre and silica fume.

They reported that flexural strength increased up to 40% when using 0.40% polypropylene fibre with the addition of 10% silica fume. This research focused on the performance of micro fine POFA as a partial cement replacement material in a mortar mix, reinforced with polypropylene fibres.

Regarding the physical qualities, microfine sized POFA has a smaller median particle size, lower specific gravity and a larger specific surface area, all of which contribute to an increased workability in fresh mortar. Microstructure analysis, load vs displacement (flexural test), split tensile strength tests and compressive strength tests were used to gather data for the study.

Materials and Methods

This investigation has predominantly focused on the application of microfine POFA as an alternative to cement in the mortar mix. The areas of focus are compressive strength, flexural strength measured by the split tensile strength, microstructure investigation and displacement ductility ratio.

Material

The raw POFA for this study was obtained from a nearby palm oil plant situated in the state of Sarawak (Bau, Lundu Palm Oil Mill) and the ash met the requirements of BS3892: Part 1-1992. The raw POFA underwent a burning process in furnace at 500°C for one hour to remove the excess carbon on the surface. The treated POFA was then sieved passing through a 75 mm sieve before being ground using electric powder grinder. The particle size of the ground burnt POFA was determined using the particle Size Analyser (CILAS 1090L).

The treated POFA's average diameter obtained at D_{50} ranges from 1 – 10 mm was used throughout the research. According to ASTM C618-15, the ash was neither class C nor F, depending on the source and the category and hence may be classified somewhere in between the C and F. The polypropylene fibre with properties as shown in Table 1 is used in this research. The aspect ratio of fibre used is in the range of 30 to 100 in accordance with ACI 544.3R-08.

Table 1: Properties of polypropylene fibre

Fibre	Length (mm)	Diameter (mm)	Specific Gravity	Tensile Strength (MPa)	Melting Point (°C)	Moisture Content (%)	Electrical Conductivity	Thermal Conductivity
Poly-propylene	25	0.6	0.92	600 – 650	160	0	Low	Low

Mixed Design

In the concrete mix, the microfine POFA is used in order to produce 50 mm^3 mortar cubes and also mortar cylinders with a height of 200 mm and diameter of 100 mm. In order to select 40% POFA replacement as optimum, various mix designs were prepared earlier by altering the POFA inclusion ranging from 0% to 60%.

From the compressive strength test conducted at 50 mm^3 cube specimens, for up to 56 days of curing, the optimum amount of POFA was found at 40% replacement. Hence, 40% amount of POFA is chosen as cement replacement material in this research.

Mortar cube samples tested two categories, whereas the first was done using 100% OPC and the second 40% POFA (60% OPC) as shown in Table 2. Under typical room temperature (27°C), the samples were totally submerged in tap water after the de-moulding following periods of 7, 14, 28 and 56 days.

The microstructure analysis was done using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) while the specimens were at 7 and 28 days of curing.

Experimental Procedures

The mechanical performance of fibre reinforced mortar will be judged on its compressive strength, flexural strength in term of ductility ratio and spilt tensile strength of the specimens. Microstructure analysis was also carried out to provide an insight into the physical characteristics of the material.

Compressive Strength Test

For this test, 50 mm^3 mortar cubes are tested at 7, 14, 28 and 56 days of curing. Mortar cube samples tested were of two categories, where the first is used 100% OPC and the second 40% POFA (60% OPC). Both categories of samples used the same water cement ratio of 0.2 and various amount of fibre inclusion (Table 2).

Table 2: Mix design of fibre reinforced mortars

Samples/Mix Design	Mix Proportion			Curing Days		
	OPC (% Volume)	Fibre (kg/m^3)	POFA (% Volume)	Compressive Strength Test	Flexural Strength Test	Split Tensile Strength Test
100OPC0F	100	-	-	7, 14, 28 & 56	28 & 56	7, 14 & 28
100OPC10F		10				
100OPC15F		15				
100OPC20F		20				
40POFA0F	60	-	40			
40POFA10F		10				
40POFA15F		15				
40POFA20F		20				

The mixing method of ASTM C 109/C109M – 02 (Machine Mixing), casting, compacting (using tamping road; tamped 25 times for each layer; 3 layers) and curing in water was carried out. Three samples of each type of mix design were tested and the average compressive strength was recorded. The optimum volume percentage of POFA and fibre inclusion was decided based on the compressive strength test results.

Flexural Strength Test

For this test, 50 mm x 50 mm x 200 mm rectangular beams were tested at 28 and 56 days of curing, based on the ASTM D1635 standard. The optimum percentage of fibres and Load vs Displacement graph were obtained from this test, consequently, the ductility ratio could be determined.

Split Tensile Strength Test

For this test, 200 mm x 100 diameter cylinders were casted at 7, 14 and 28 days of curing, based on IS 5816 (1999). The optimum amount of fibre was obtained using this test.

Microstructure Analysis

Microstructure analysis using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) was employed to further explore the mechanical behaviour of Fibre Reinforced Mortar (FRM).

Results and Discussion

Compressive Strength

The results for samples of mix design for both categories using 40% POFA (60% OPC) and 0% POFA (100% OPC) with various amount of fibre inclusions is listed in Table 3. The trend of compressive strength results for comparison between both mix design categories is shown in Figure 1 and Figure 2.

The compressive strength of the 56 days 100% OPC sample showed that 100OPC20F mortar achieved the highest strength which was 82.4MPa, 1.2% higher than 100OPC15F, 2.3% higher than 100OPC10F and 7.4% higher than 100OPC0F. However, the compressive strength of 56 days 40% POFA sample showed that the 40POFA10F mortar achieved the compressive strength of 79.5MPa which is 1% higher than 40POFA20F, 1.5% higher than 40POFA15F and 7.2% higher than 40POFA0F.

The strength increment for the FRM with 40% POFA was slower when compared to the FRM mixed with 100% Ordinary Portland Cement (OPC). The mortar with POFA develops early strength at a rate lower than that containing 100% OPC due to presence of higher OPC which resulted in a higher early strength in the latter. The hydration process took longer when the cement was mixed with POFA.

The degree of fineness of POFA has an influence on the compressive strength of the

Table 3: Average values of compressive strength for OPC and POFA, with inclusion of fibres

100% OPC with Fibres (Control)					40% POFA with Fibres			
Fibre Dosage Inclusion	Days of Curing							
	7th	14th	28th	56th	7th	14th	28th	56th
	Compressive Strength (MPa)							
0 kg/m^3	57.1	69.8	76.3	79.1	48.5	68.0	70.8	73.8
10 kg/m^3	59.1	71.3	79.8	80.5	54.8	74.6	76.0	79.5
15 kg/m^3	58.7	69.6	79.4	81.2	51.9	66.1	76.4	78.3
20 kg/m^3	56.8	66.8	75.4	82.4	50.8	63.5	74.3	78.7

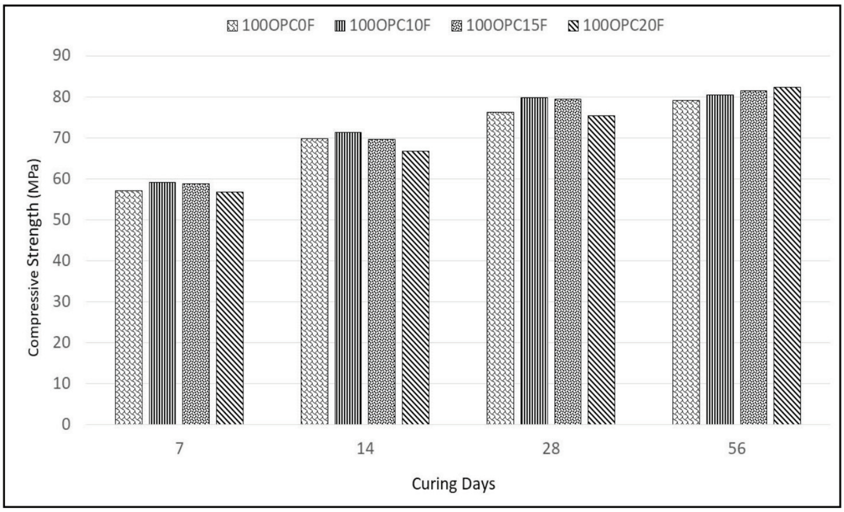

Figure 1: Compressive strength of OPC with inclusion of fibres

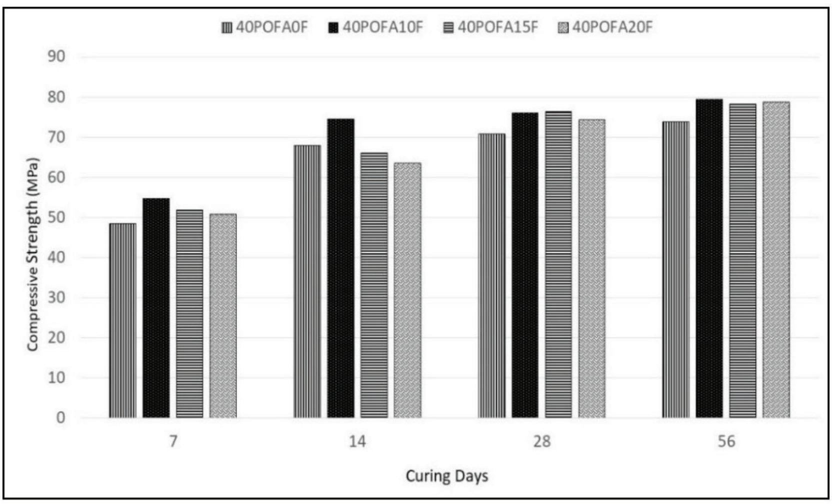

Figure 2: Compressive strength of OPC with POFA and fibres inclusions

mortar. This can be observed by comparing the compressive strength at 28-day for 100% OPC and 40% POFA. The latter exhibits a slightly lower value of average compressive strength almost close to the former, mainly due to the larger surface area of particles that was affected by pozzolanic activity and hence the strength (Al-Mulali *et al.,* 2015).

POFA particles' fineness aids in the filling of spaces between the cement and aggregates. While the hydration process takes place, excess calcium silicate hydrate is formed due to the reaction between $Ca(OH)_2$ and SiO_2 from the POFA. According to Karim *et al.* (2011), later, this extra calcium silicate hydrate can help strengthen the interfacial bonding between the pastes and the aggregates. This property has been found to improve the concrete's compressive strength along with its density.

The results also show that adding 20 kg/m^3 of polypropylene fibre, increases the compressive strength reaching up to 82.4MPa (100% OPC-

56 days) and 78.7MPa (40% POFA as partial cement replacement-56 days), respectively.

The intensification in compressive strength for sample with 20 kg/m^3 fibre addition may be due to the crosswise incarceration effect of polypropylene fibre. The fibres restrain the expansion of the mortar cube samples which may help in resisting the development of microcracks (Lee *et al.,* 2015). After microcracking, fibres are known to boost energy absorption capacity, which is dependent on the amount of fibre and the bonding of the composite mixture.

Adding an optimum amount of fibre to a well bonded mixture can knowingly reduce the development of microcracks. In contrast, for samples with 40% POFA with fibre inclusion of 15 kg/m^3 and 20 kg/m^3, respectively, the compressive strength of mortar cube samples slightly decreased to 78.3 MPa and 78.7 MPa, respectively.

This can be observed from Figure 2 whereas the increase in fibre inclusion had reduced the compressive strength of mortar, although it was not very significant. The loss in compressive strength is caused by a rise in voids and matrix disturbance. Furthermore, to the amount of fibre, perturbation is influenced by the matrix's ability to accept the fibres (Neves *et al.,* 2005). Therefore, it can be concluded that the addition of fibres could provide a balance in bridging the microcracks.

Flexural Strength Test (Ductility Ratio)

Flexural strength tests were carried out to determine the displacement ductility ratio of the mortar. A total of 32 rectangular beams of size 50 mm x 50 mm x 200 mm were cast and allowed to cure over a period of 28 and 56 days. The displacement ductility ratio was calculated using Equation 1. Table 4 shows the result of ductility ratio for samples with and without fibres respectively.

Displacement Ductility Ratio, $\mu = \Delta u / \Delta y$ (Equation 1)

whereby:

Δ_u = Deflection at ultimate point
Δ_y = Deflection at yield point

The results show that the samples with combination of 40% POFA and 10 kg/m^3 of fibres, gave the highest displacement ductility ratio, 7.3 and 13.3 for 28 and 56 days, respectively. It appears that this is due to the amount of fibre added in addition to the shock absorbent nature of the Palm Oil Fuel Ash. A similar pattern was observed by Teo (2006) whereby the OPS beams toughness and shock absorbance helped in improving the ductility of the mix. The sample with a 100% OPC shows a relatively low ductility value at 28 days compared to the sample with 40% POFA. This is probably due to the brittle nature of the mortar. However, the 100% OPC sample showed a slight increment in the ductility

Table 4: Displacement ductility ratio

	Ductility Ratio	
Without Fibre	**28 days**	**56 days**
100OPC0F	4.3	5.2
40POFA0F	6.5	7.0
With Fibre	**28 days**	**56 days**
100OPC10F	5.0	7.5
100OPC15F	4.7	7.2
100OPC20F	3.5	6.3
40POFA10F	**7.3**	**13.3**
40POFA15F	7.8	12.0
40POFA20F	6.8	8.3

ratio after 56 days because of the reaction between the concrete mix and the fibre surface. It can be concluded that 10 kg/m^3 and 15 kg/m^3 fibres mixed with 40% POFA develop the highest ductility value at 56 days, 13.3 and 12, respectively. Figure 3 shows the samples after the ductility test after 28 days curing time.

Split Tensile Strength Test

Figure 4 depicts the results of a split tensile strength on a mortar cylinder with a 100% OPC and 40% POFA as a partial cement replacement with no fiber (control) while Figure 5 shows the results with fibre inclusion of 10 kg/m^3, 15 kg/m^3 and 20 kg/m^3. The tensile reading for samples that have fibre inclusion are higher than the control samples that are without fibre.

It is anticipated that the combination of POFA and Polypropylene fibre contributes to the development of the mortar split tensile strength. For example, tensile strength mixture of 40% POFA at 7 days started at 4.5 MPa for 10 kg/m^3, 4.8 MPa for 15 kg/m^3 and 4.0 MPa for 20 kg/m^3. These results showed that the samples containing POFA have slow early strength development. Slow rates of strength development at early stages of curing due to the pozzolanic nature of the POFA.

Figure 3: Sample after 28 days of curing age

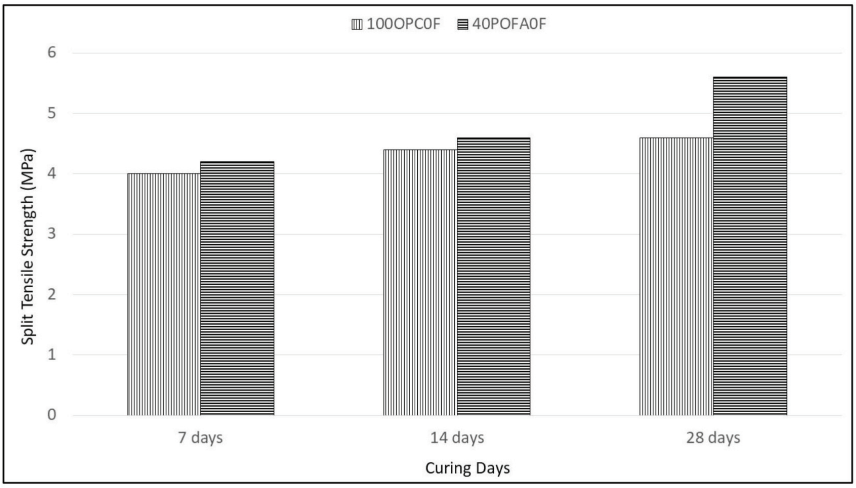

Figure 4: Obtained results split tensile without fibres

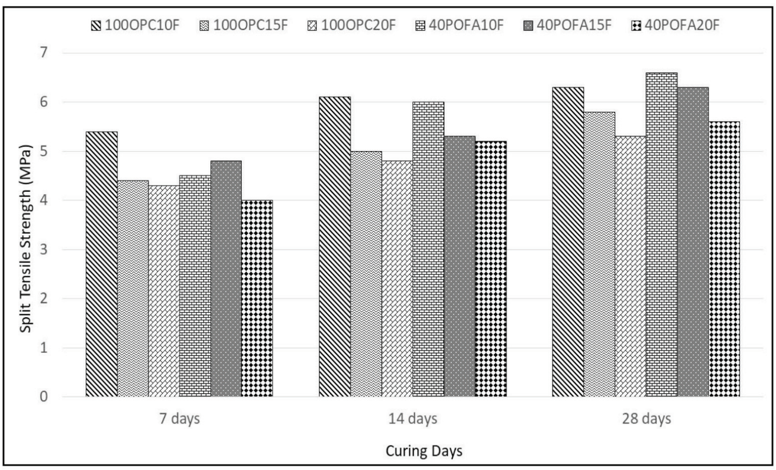

Figure 5: Obtained results split tensile with fibres

It is known that the size of POFA used in this study is less than 10 µm. The void filling effect from the POFA particles increased the surface area of interaction between the fibre and the aggregate mix. The high pozzolanic reaction of POFA, (which rises with time) results in an increased amount of hydration product (Awal *et al.,* 2016).

According to Tangchirapat (2009), higher fineness of POFA can minimise the permeability of concrete, resulting in less degrees of expansion and degradation of compressive strength when compared to a sample mix containing 100% OPC.

A 10 kg/m^3 inclusion of fibre provides the premier strength for both mix, 6.3 MPa (100% OPC) and 6.6 MPa (40% POFA). The outcomes indicate that the fibre influences the strength performance of the mortar. Fibre with higher tensile strength properties is more likely to transfer tensile stress from cracked section to fibre (Awal *et al.,* 2016). Ibnul *et al.* (2016) stated that substantial failure and cracks can develop when loads are applied to concrete that is not reinforced.

On the other hand, concrete containing fibre in its mix can withstand further crack propagation. Any crack propagation reduces the effective stiffness of the concrete matrix. Following significant cracking, the tensile stress is then transferred and resisted by the polypropylene fibre. The fibre supports the tensile stress by acting as a bridge to the microcracks. Transferring the stress to the fibre ultimately improves the tensile strain ability of a fibrous concrete matrix compared to a non-fibrous mixture (Awal *et al.,* 2016).

Microstructure Analysis of Fibre Reinforced Mortar

The Scanning Electron Microscopy (SEM) was performed to illustrate the morphology and microscopic features of the mortar containing cementitious material and polypropylene fibres. The 28-day samples were studied under the SEM imaging to understand the effects of polypropylene fibres and POFA on the performance of mortar. In Figure 6 (a), the bridging action between the fibre and mortar composites starts to develop on the 7th day. Compared to Figure 6 (b), at the 28th day, the polypropylene fibre along with the mortar provide a strong bond after rupture.

There is also a reduction in the cracks size on the interface, this is consistent with the results reported by Mohammadhosseini *et al.* (2016). As mentioned by Wu *et al.* (2013), the hydration process tends to develop during the curing age of seven days, hence, there is less bonding between the fibre and cement which causes cracks to develop.

However, the bonding between the fibre and cement increases and less cracks are formed at the curing age of 28 days. Figure 6 (b) also shows that the bonds between the fibre and the mortar become more developed and stronger as curing continues.

The presence of the polypropylene fibre in the mortar acts as a bridging force across the cracks. They also reduce micro cracks and improve the microstructure of the mortar.

EDX was analyzed by taking ten points in each sample with the same SEM image. The major elements present in each sample were analyzed such as C, O, Na, Mg, Al, N, Si, S, K, Ca and Fe. However, silica (Si) and calcium (Ca) were considered the two main elements of the hydrated binder. Table 5 indicates that CaO/SiO_2 ratio tends to increase with the addition of POFA as a cement replacement.

The result showed that the CaO/SiO_2 ratio as 1.41 with 40% of POFA with the addition of polypropylene fibres. Ahmadi *et al.* (2018) also used 40% POFA as a cement replacement for the cement paste and found that the Ca/SiO_2 ratio was 1.70 which was similar to the results of the present analysis. As polypropylene fibres do not react with any chemical composition, the

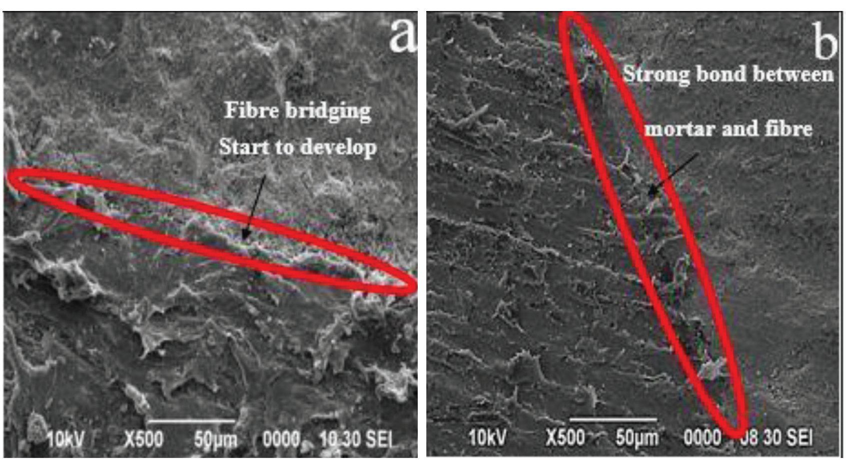

Figure 6: Micrographs of 40% POFA with polypropylene fibres at (a) 7th days and (b) 28th days

Table 5: Ratio of CaO/SiO_2 in each sample from EDX analysis

Samples		Element (mass as oxide %)		CaO/SiO_2 Ratio
		Calcium Oxide (CaO)	Silica Oxide (SiO_2)	
Raw material	Unburned POFA	0.23	0.72	0.32
	Burned POFA	0.34	0.64	0.53
Control sample	7th days	0.52	0.39	1.33
	28th days	0.53	0.38	1.39
60% OPC + 40% of POFA + 10 kg/m³ of polypropylene fibre				
7th days	EDX on polypropylene fibre	0.39	0.39	1.00
	EDX on mortar surface	0.51	0.41	1.24
28th days	EDX on polypropylene fibre	0.24	0.23	1.04
	EDX on mortar surface	0.55	0.39	1.41

binding of the fibre with the surface is due to the reaction and formation of C-S-H gel. Fibre bridging starts to develop strong bonds between the mortar and the fibre composition.

The surface change of the polypropylene fibre is dependent on the composition of the fibre and the test conditions applied. The results in Table 5 showed that silica oxide is the main composition in POFA which contributes to the pozzolanic reaction.

Conclusion

This research focused on the creation of a high strength fibre reinforced mortar with the inclusion of microfine POFA ranging from 1 – 10 μm as a partial cement replacement in mortar. Tests for the flexural strength, compressive strength, split tensile and SEM/EDX were conducted to determine the performance of fibres inclusion on the mechanical strength of the mortar. Results on the compressive strength of the mortar that contained 40% micro-fine POFA mixed with 10 kg/m^3 of polypropylene fibre gave the highest values of compressive strength, 79.5MPa at 56 days of curing which achieved the targeted high strength mortar properties.

Hence, the optimum fibre reinforced mortar in terms of compressive strength would be 40% micro-fine POFA with 10 kg/m^3 fibres which showed a relatively good ductility ratio value up to 13.3. Scanning Electron Microscopy (SEM) results showed a good fibre-mortar bond in the morphology of the samples at 7 and 28 days.

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